Measurement of $\Xi^- \to \Lambda\pi^-$ and $\Omega^- \to \Lambda K^-$ Decay Parameters

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Why We Measure Decay Parameters?

- A nonleptonic hyperon decay, $B_i \to B_f\ X$, is described by three decay parameters (B and X represent a baryon and a spin-zero meson respectively):

$$\alpha_H = \frac{2Re(A^*_{J-\frac{1}{2}} A_{J+\frac{1}{2}})}{|A_{J-\frac{1}{2}}|^2 + |A_{J+\frac{1}{2}}|^2}, \quad \beta_H = \frac{2Im(A^*_{J-\frac{1}{2}} A_{J+\frac{1}{2}})}{|A_{J-\frac{1}{2}}|^2 + |A_{J+\frac{1}{2}}|^2}, \quad \gamma_H = \frac{|A_{J-\frac{1}{2}}|^2 - |A_{J+\frac{1}{2}}|^2}{|A_{J-\frac{1}{2}}|^2 + |A_{J+\frac{1}{2}}|^2}.$$

- For $J = \frac{1}{2}$($J = \frac{3}{2}$), $A_{J-\frac{1}{2}}$ and $A_{J+\frac{1}{2}}$ are amplitudes of S-wave(P-wave) and P-wave(D-wave), and correspond to parity-violating(parity-conserving) and parity-conserving(parity-violating) states respectively;

- $\Xi \to \Lambda\pi$ decays: $\alpha_\Xi = \frac{2Re(S^*P)}{|S|^2 + |P|^2}, \quad \beta_\Xi = \frac{2Im(S^*P)}{|S|^2 + |P|^2}, \quad \gamma_\Xi = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}.$

- $\Lambda \to p\pi$ decays: $\alpha_\Lambda = \frac{2Re(S^*P)}{|S|^2 + |P|^2},$

- $\Omega \to \Lambda K$ decays: $\alpha_\Omega = \frac{2Re(P^*D)}{|P|^2 + |D|^2}.$

$\Xi \to \Lambda\pi$ decays

- CP**-violation in the** $\Xi \to \Lambda\pi$ **decay can be probed by the asymmetry**

$$A_\Xi = -\underbrace{\tan(\delta_p - \delta_s)}_{strong}\underbrace{\sin(\phi_p - \phi_s)}_{weak}. \tag{1}$$

If *CP*-violating weak phases are negligible, $\delta_p - \delta_s$ can be determined through

$$\frac{\beta_\Xi}{\alpha_\Xi} = \tan(\delta_p - \delta_s) \tag{2}$$

Thus measuring β_Ξ **and** α_Ξ **is equivalent to measuring** $\delta_p - \delta_s$.

- **Theoretical Predictions**

Theory	$\delta_p - \delta_s$ (degree)
R. Nath (1965)	$\delta_p - \delta_s \approx 16$
M. Lu et al. (1994)	$\delta_p - \delta_s = -1.7$
A. Kamal (1998)	$-4.2 < \delta_p - \delta_s < -1.4$
A. Datta et al.(1998)	$-3.3 < \delta_p - \delta_s < 0.9$
U. Meissner and J. Oller (2001)	$-2.8 < \delta_p - \delta_s < -1.7$
J. Tandean et al. (2001)	$-3.9 < \delta_p - \delta_s < 7.8$

$\Omega \to \Lambda K$ decays

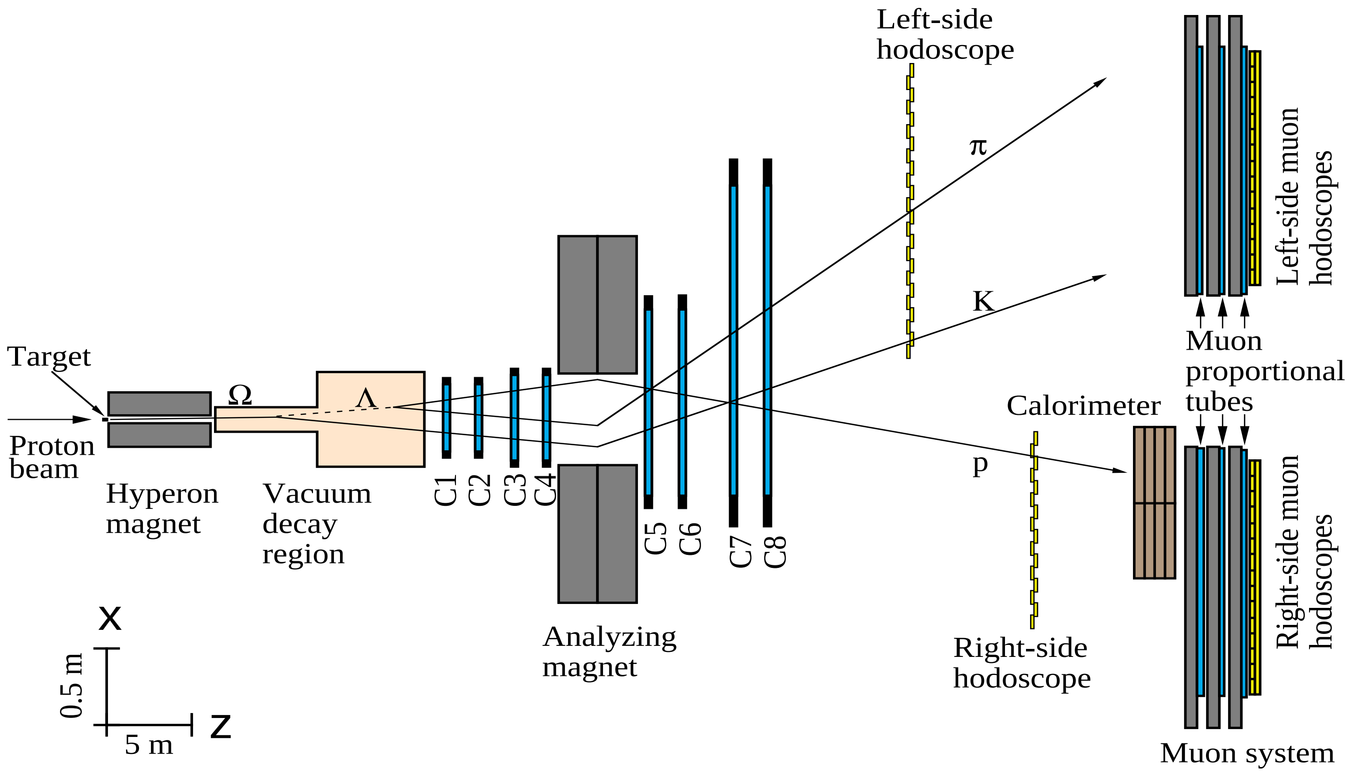
- Theoretically, D-wave is kinematically suppressed and α_Ω is expected to be zero (M. Suzuki, 1964). Non-zero α_Ω indicates parity violation in this decay.
- A difference between $|\alpha_\Omega|$ and $|\alpha_{\overline{\Omega}}|$ would be evidence of CP violation.
- Previous experimental results for α_Ω are **consistent with zero**.

Experiment	Year	Events	α_Ω
CERN-SPS	1984	12,000	-0.025 ± 0.028
FNAL E620	1988	1,743	-0.034 ± 0.079
FNAL E756	1998	6,953	-0.028 ± 0.047
PDG Average			-0.026 ± 0.023

- *HyperCP* has collected the largest samples of hyperon decays in the world which allows precise measurements of decay parameters.

The *HyperCP* (E871) Spectrometer

- Protons on target $= (7 \sim 8)$ GHz
- Secondary beam intensity $= (10 \sim 15)$ MHz
- Trigger rate $= (50 \sim 80)$ KHz
- Charge of Sec. beam selected by the sign of Hyperon magnet



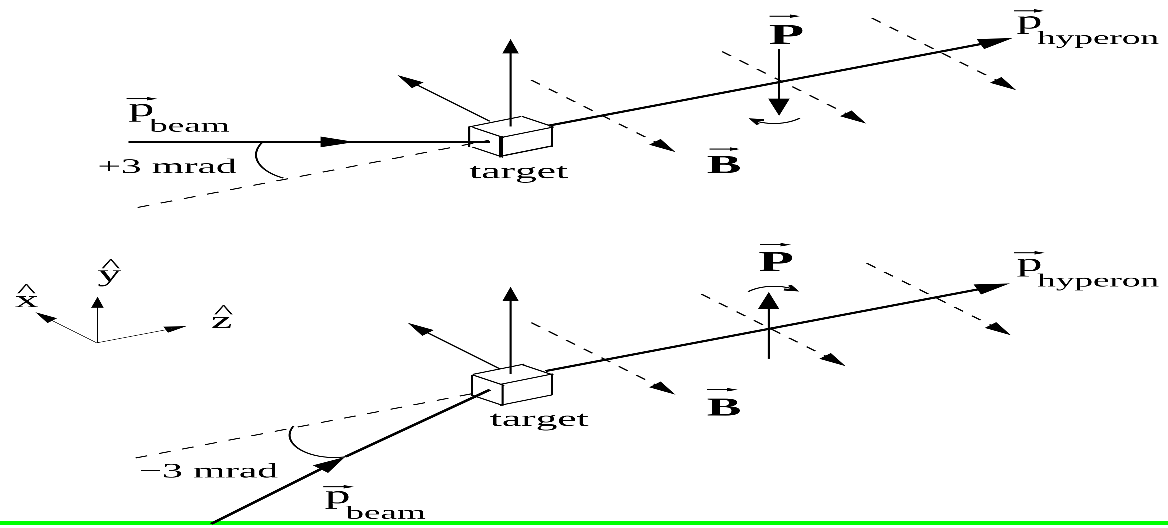
Measuring β_Ξ, γ_Ξ

- We use polarized $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$ decays, where the angular distribution of the joint decay has the form

$$\frac{d^2N}{d\Omega_\Lambda d\Omega_p} = \frac{1}{(4\pi)^2}(1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda})(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{p}), \tag{3}$$

where

$$\vec{P}_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{\Lambda})\hat{\Lambda} + \beta_\Xi(\vec{P}_\Xi \times \hat{\Lambda}) + \gamma_\Xi \hat{\Lambda} \times (\vec{P}_\Xi \times \hat{\Lambda})}{1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda}}. \tag{4}$$

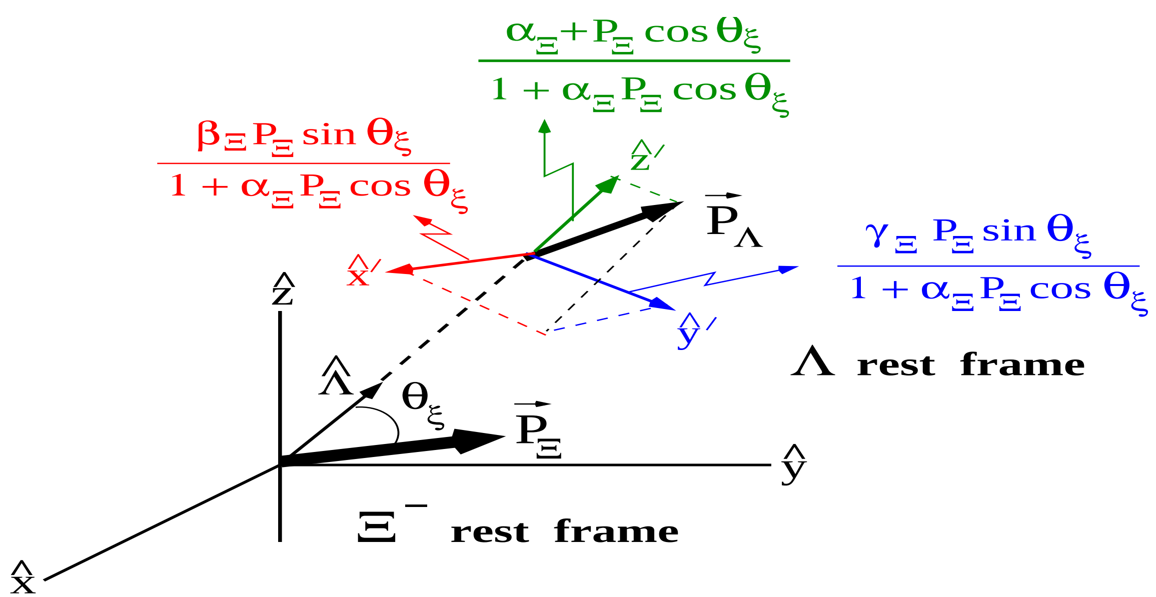


- In the coordinate system defined as

$$\hat{z}' = \hat{\Lambda}, \quad \hat{x}' = \frac{\vec{P}_{\Xi} \times \hat{\Lambda}}{|\vec{P}_{\Xi} \times \hat{\Lambda}|}, \quad \hat{y}' = \hat{z}' \times \hat{x}', \tag{5}$$

Λ polarization is determined as

$$\vec{P}_{\Lambda} = \left(\frac{\beta_{\Xi} P_{\Xi} \sin\theta_{\xi}}{1 + \alpha_{\Xi} P_{\Xi} \cos\theta_{\xi}}, \frac{\gamma_{\Xi} P_{\Xi} \sin\theta_{\xi}}{1 + \alpha_{\Xi} P_{\Xi} \cos\theta_{\xi}}, \frac{\alpha_{\Xi} + P_{\Xi} \cos\theta_{\xi}}{1 + \alpha_{\Xi} P_{\Xi} \cos\theta_{\xi}}\right)$$



- Proton angular distributions with respect to $\hat{z}'$, $\hat{x}'$, and $\hat{y}'$ in Λ rest frame are respectively as

$$\frac{d^2N}{d\Omega_\Lambda d\cos\theta_{pz'}} = \frac{1}{8\pi}[(1+\alpha_\Xi \vec{P}_\Xi \cdot \hat{\Lambda}) + \alpha_\Lambda(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{\Lambda})\cos\theta_{pz'}], \tag{6}$$

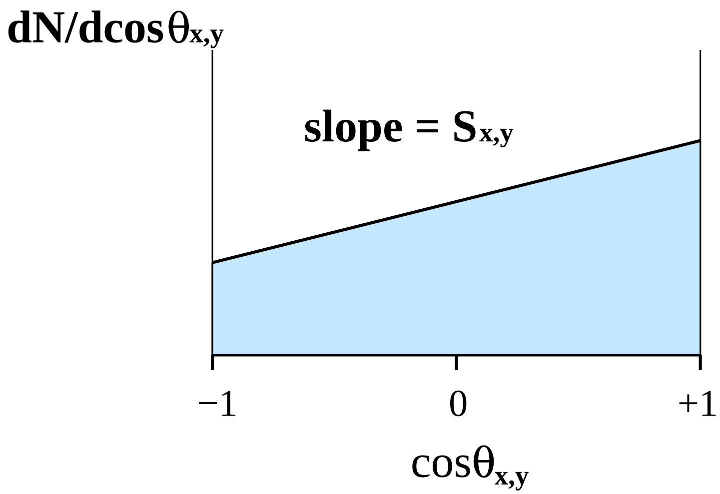
$$\frac{dN}{d\cos\theta_{px'}} = \frac{1}{2}(1 + \underbrace{\frac{\pi}{4}\alpha_\Lambda \beta_\Xi P_\Xi}_{S_x} \cos\theta_{px'}), \tag{7}$$

$$\frac{dN}{d\cos\theta_{py'}} = \frac{1}{2}(1 + \underbrace{\frac{\pi}{4}\alpha_\Lambda \gamma_\Xi P_\Xi}_{S_y} \cos\theta_{py'}), \tag{8}$$

where $\cos\theta_{pz'} = \hat{p}\cdot\hat{z}'$, $\cos\theta_{px'} = \hat{p}\cdot\hat{x}'$, $\cos\theta_{py'} = \hat{p}\cdot\hat{y}'$.

Eqs. (6), (7), and (8) allow us to measure $\vec{P}_\Xi$, β_Ξ, and γ_Ξ.

- β_Ξ and γ_Ξ can be extracted from the slopes of Eqs. (7) and (8), S_x and S_y.



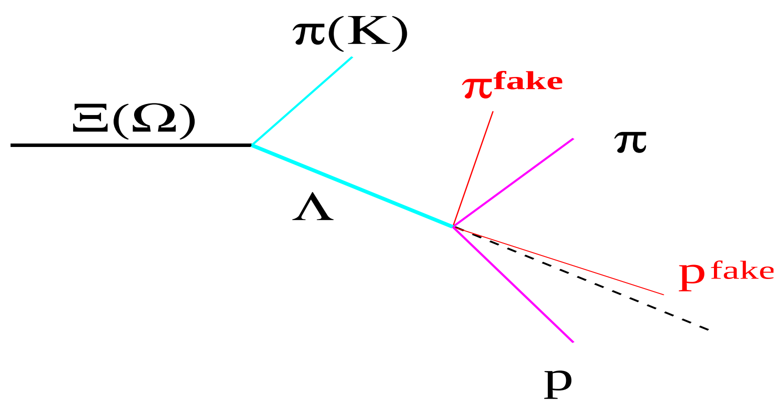
- Since $\alpha_\Xi^2+\beta_\Xi^2+\gamma_\Xi^2 = 1$, $(\phi_\Xi,\beta_\Xi,\gamma_\Xi)$ is alternatively used to describe $\Xi \to \Lambda\pi$ decays

$$\beta_\Xi = \sqrt{1-\alpha_\Xi^2}\sin\phi_\Xi, \quad \gamma_\Xi = \sqrt{1-\alpha_\Xi^2}\cos\phi_\Xi. \tag{9}$$

where

$$\tan\phi_\Xi = \frac{\beta_\Xi}{\gamma_\Xi} = \frac{S_x}{S_y} \tag{10}$$

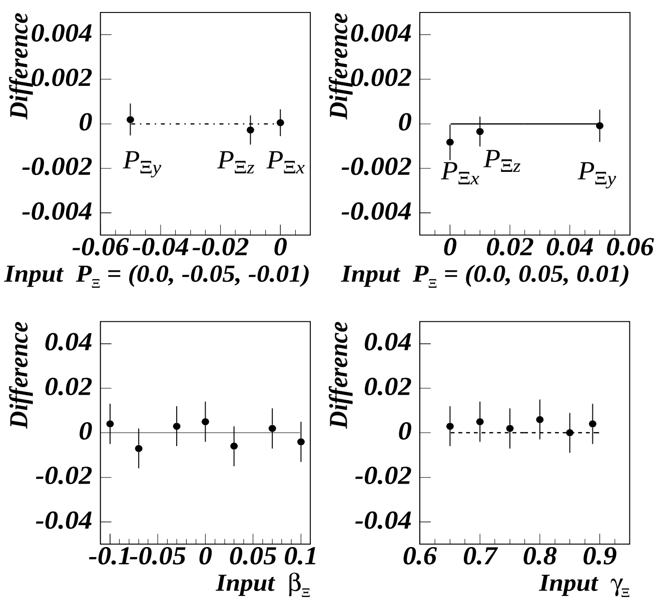
Hybrid Monte-Carlo Method (HMC)

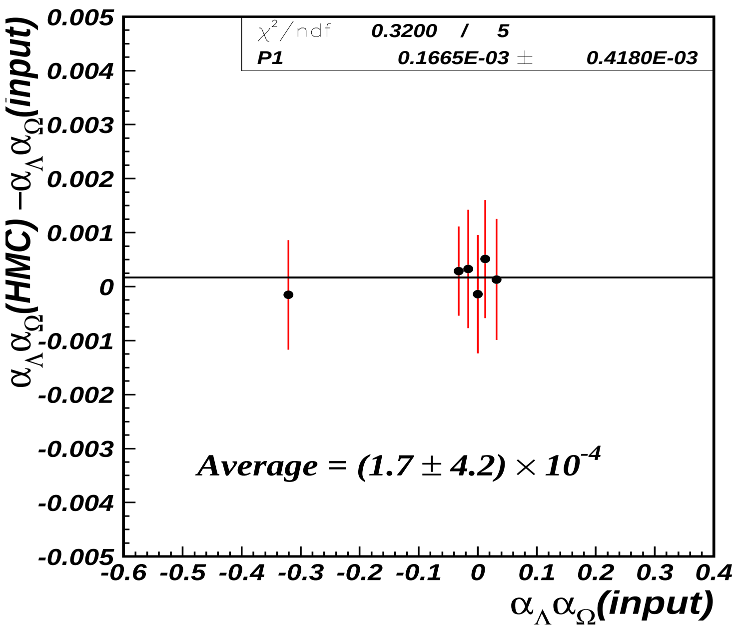


- In reality, $\cos\theta$ distribution is distorted by the spectrometer acceptance, which can be measured by Monte-Carlo.
- Take all variables from each real event except $\cos\theta$.
- Generate **HMC events** with uniform $\cos\theta$.
- Let all the **HMC events** go through the software spectrometer, triggers, etc.; hence determine the acceptance.
- Weight **HMC events** to match the angular distributions of real and HMC events to obtain $\vec{P}_{\Xi}$, β_{Ξ}, γ_{Ξ}, and $\alpha_{\Omega}\alpha_{\Lambda}$.

Validation of HMC

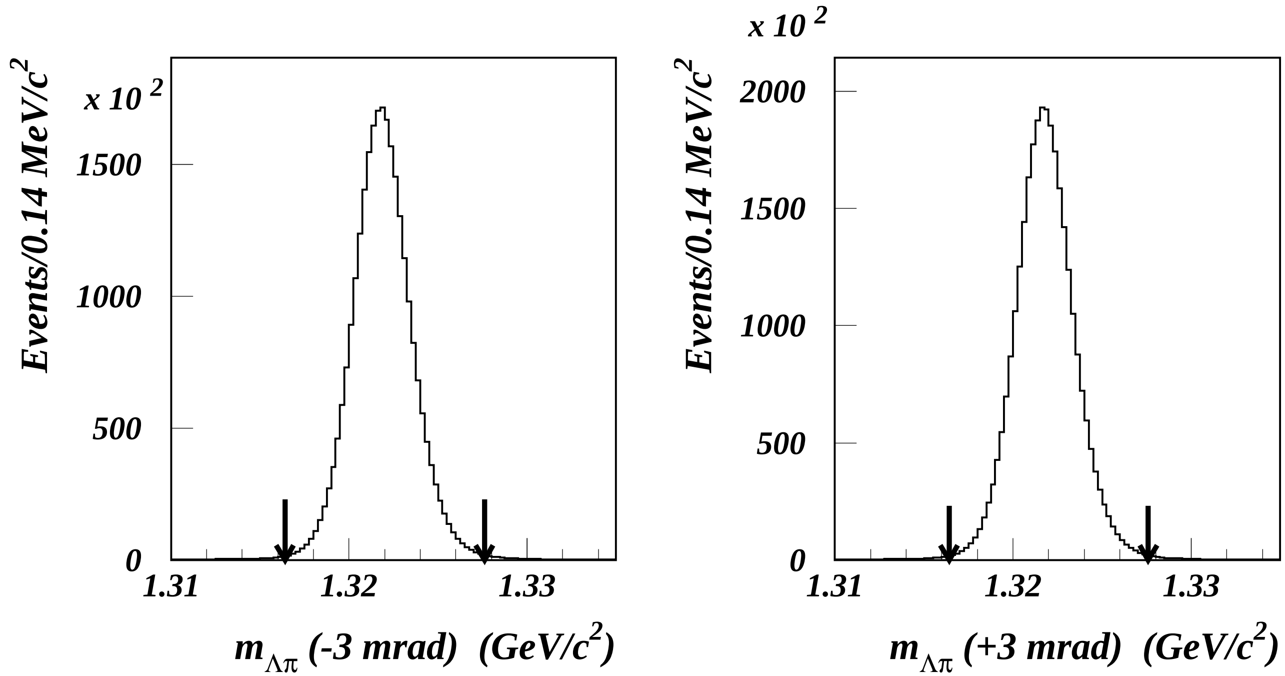
- Generated Monte-Carlo samples with different input values of $\vec{P}_\Xi$, β_Ξ, γ_Ξ, and $\alpha_\Omega\alpha_\Lambda$.
- Analyzed these Monte-Carlo samples with HMC to obtain the measurement values of $\vec{P}_\Xi$, β_Ξ, γ_Ξ, and $\alpha_\Omega\alpha_\Lambda$, and compare the difference between measurement and input values.



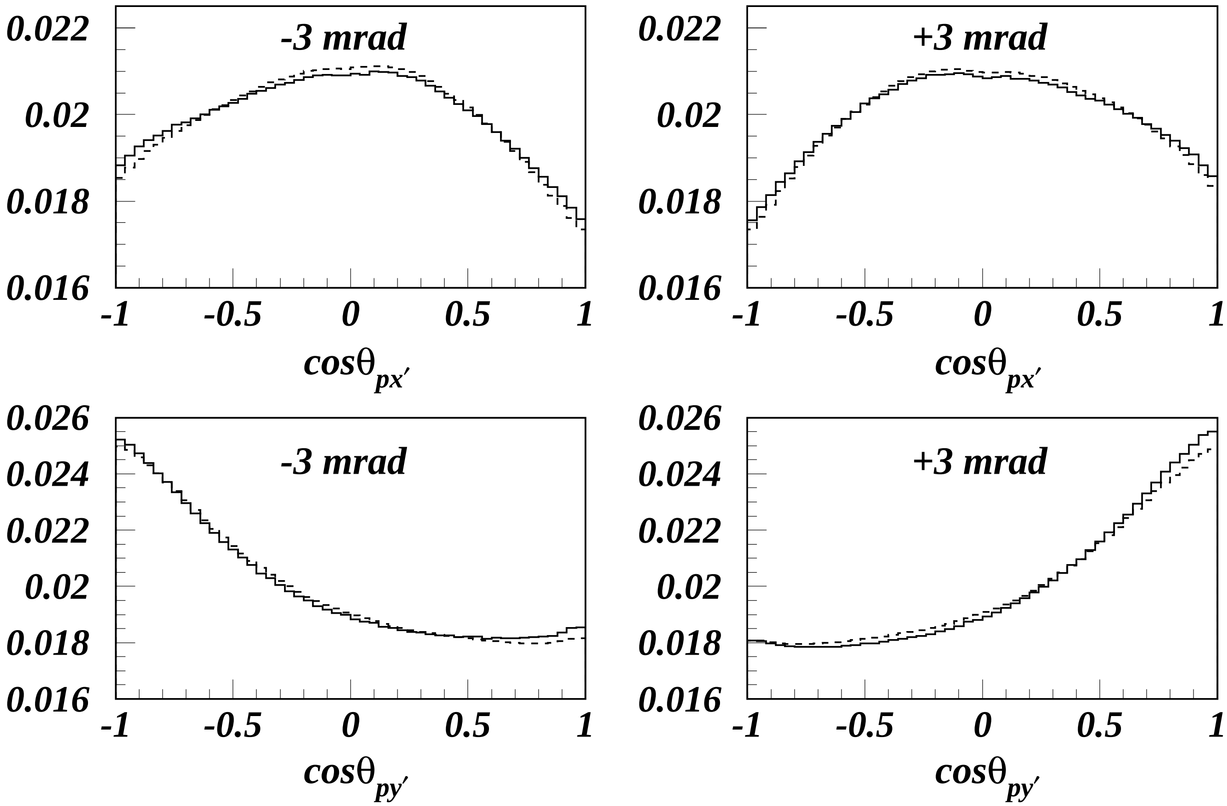


Results of ϕ_Ξ, β_Ξ and γ_Ξ

- 60 million $-3\ mrad$ and 72 million $+3\ mrad$ of polarized Ξ^- events after all event selection cuts were applied for the measurements.



- **Proton $\cos\theta_{px'}$ and $\cos\theta_{py'}$ distributions for data and HMC**



- **Results of ϕ_Ξ, β_Ξ and γ_Ξ**

p_Ξ (GeV/c)	S_x	S_y	ϕ_Ξ (degree)
139	-0.00037 ± 0.00047	0.01191 ± 0.00041	-1.77 ± 2.28
152	-0.00046 ± 0.00047	0.01447 ± 0.00038	-1.81 ± 1.88
162	-0.00038 ± 0.00041	0.01557 ± 0.00035	-1.39 ± 1.49
173	-0.00074 ± 0.00040	0.01880 ± 0.00036	-2.26 ± 1.22
191	-0.00123 ± 0.00040	0.02109 ± 0.00040	-3.33 ± 1.08
Average			-2.39 ± 0.64

Using $\alpha_\Xi = -0.458 \pm 0.012$ from PDG, and

$$\beta_\Xi = \sqrt{1-\alpha_\Xi^2}\sin\phi_\Xi \quad \text{and} \quad \gamma_\Xi = \sqrt{1-\alpha_\Xi^2}\cos\phi_\Xi,$$

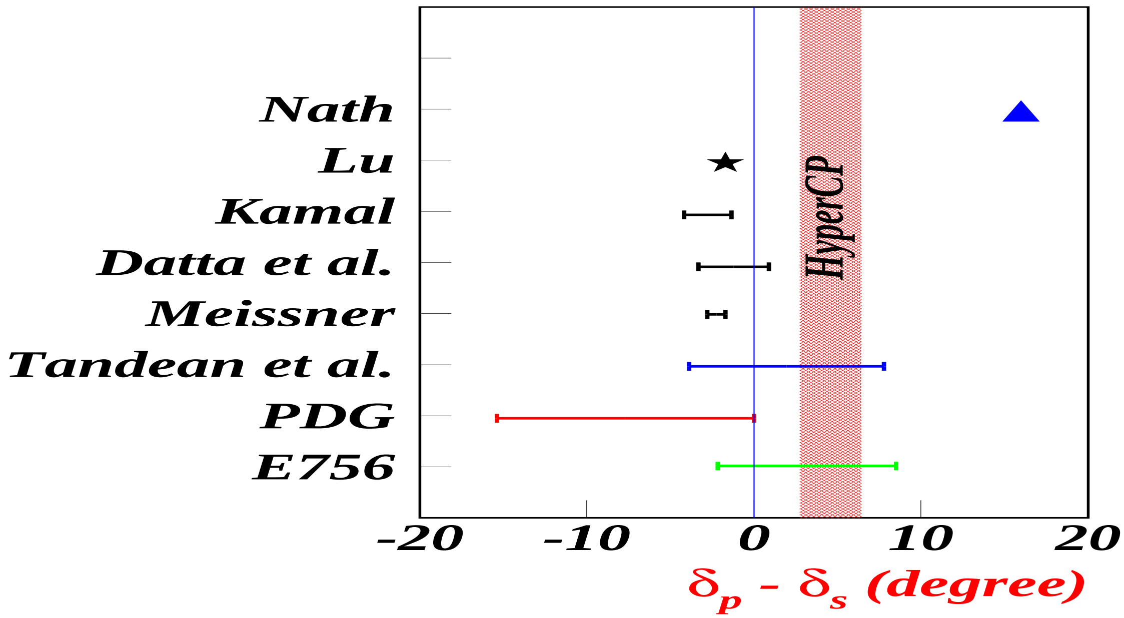
we get

$$\beta_\Xi = -0.037 \pm 0.011(stat) \pm 0.010(syst),$$

$$\gamma_\Xi = 0.888 \pm 0.0004(stat) \pm 0.006(syst)$$

$$\delta_p - \delta_s = \tan^{-1}(\frac{\beta_\Xi}{\alpha_\Xi}) = [4.6 \pm 1.4(stat) \pm 1.2(syst)]^\circ$$

- **Comparison With Other Results**
  - Chiral perturbation theory seems to have the wrong sign and small magnitude.
  - $\delta_p - \delta_s$ is about a factor of 0.6 relative to the one of $p\pi$ scattering.
  - CPV in $\Xi \to \Lambda\pi$ is smaller than that in $\Lambda \to p\pi$ but not negligible if strong phase-shift difference is considered only.



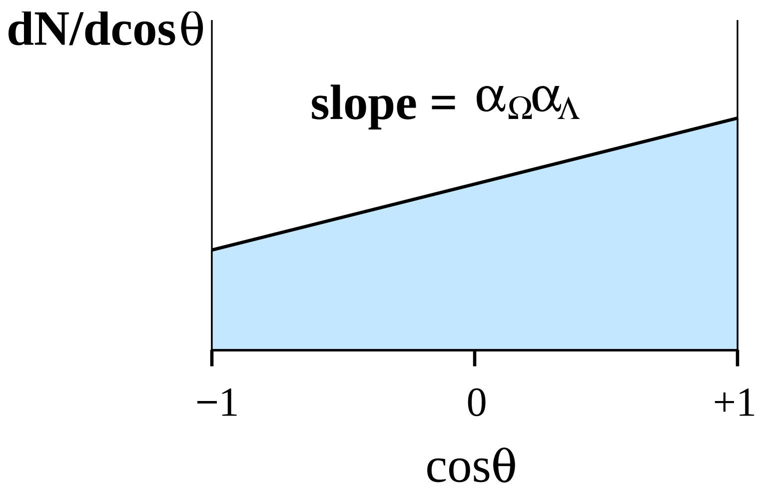
Measuring α_Ω

- For $\Omega \to \Lambda K, \Lambda \to p\pi$ decays, the proton angular distributions with respect to $\hat{z}'$, $\hat{x}'$, and $\hat{y}'$ in Λ rest frame have the same form as those of the Ξ, except that those with respect to $\hat{x}'$ and $\hat{y}'$ have additional tensor polarization terms because $J = \frac{3}{2}$.

- To measure α_Ω, we use *unpolarized* $\Omega \to \Lambda K$ events. Hence the terms associated with β_Ω and γ_Ω vanish, and the proton angular distribution is simplified as ($\cos\theta \equiv \cos\theta_{pz'}$)

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + \underbrace{\alpha_\Omega \alpha_\Lambda}_{S_m} \cos\theta). \tag{11}$$

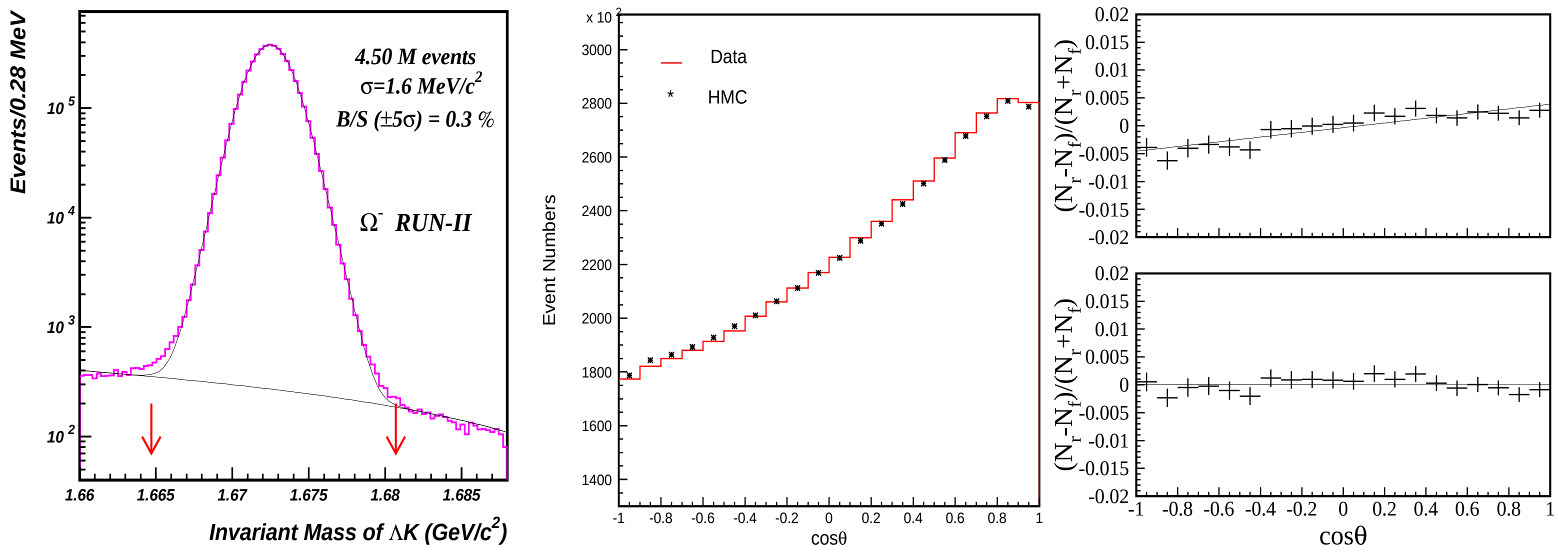
- Measuring the slope of the proton $\cos\theta$ distribution gives us $\alpha_\Omega \alpha_\Lambda$



- α_Ω can be extracted by using the parameter α_Λ of $\Lambda \to p\pi$ decays from PDG, $\alpha_\Lambda = 0.642 \pm 0.013$.

Results of α_Ω

- **After all event selection cuts, 4.5 million from RUN-II $\Omega^- \to \Lambda K^-$ events were used to measure α_Ω.**



- **Slope of proton angular distribution S_m was extracted using HMC,**

$$S_m = (1.16 \pm 0.12) \times 10^{-2}$$

- **Background slope S_b was measured from mass sidebands,**

$$S_b = (7.17 \pm 3.04) \times 10^{-2}.$$

- **Using $\alpha_\Omega \alpha_\Lambda = \frac{N_m}{N_s} S_m - \frac{N_b}{N_s} S_b$ to subtract background, we get**

$$\alpha_\Omega \alpha_\Lambda = [1.14 \pm 0.12(stat)] \times 10^{-2}.$$

- **Systematic Errors**

Systematic Study	$\lvert \alpha_\Omega \alpha_\Lambda - (\alpha_\Omega \alpha_\Lambda)_{basic} \rvert$
π_Λ decays in flight	negligible
Event selection cuts	0.09×10^{-2} (0.73σ)
Inefficiencies of spectrometer	negligible
BM109 field	negligible
HMC validation	0.04×10^{-2} (0.33σ)
Total	0.10×10^{-2}

- **Results of $\alpha_\Omega \alpha_\Lambda$ and α_Ω**

  Together with the results from the analysis of 1 million events on RUN-I data, our results are:

$$\alpha_\Omega \alpha_\Lambda = [1.18 \pm 0.29(\mathrm{stat})] \times 10^{-2} \text{ (RUN-I)},$$

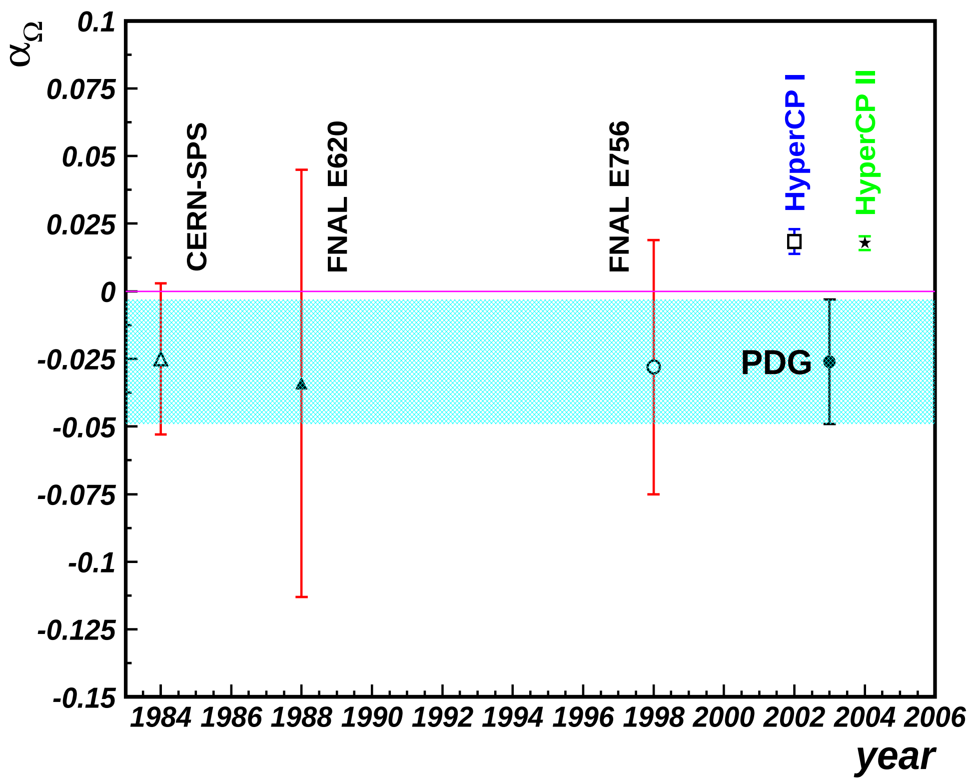
$$\alpha_\Omega \alpha_\Lambda = [1.14 \pm 0.12(\mathrm{stat}) \pm 0.10(\mathrm{syst})] \times 10^{-2} \text{ (RUN-II)}.$$

  Using PDG value $\alpha_\Lambda = 0.642 \pm 0.013$, we get

$$\alpha_\Omega = [1.84 \pm 0.46(\mathrm{stat})] \times 10^{-2} \text{ (RUN-I)},$$

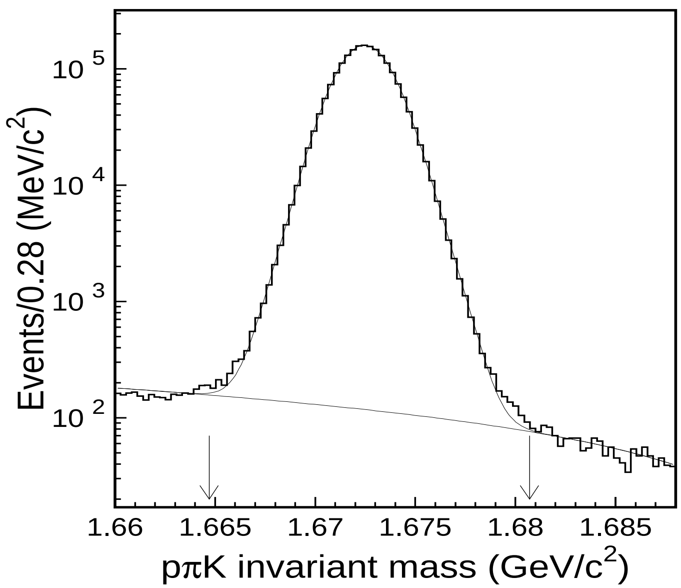
$$\alpha_\Omega = [1.78 \pm 0.19(\mathrm{stat}) \pm 0.16(\mathrm{syst})] \times 10^{-2} \text{ (RUN-II)}.$$

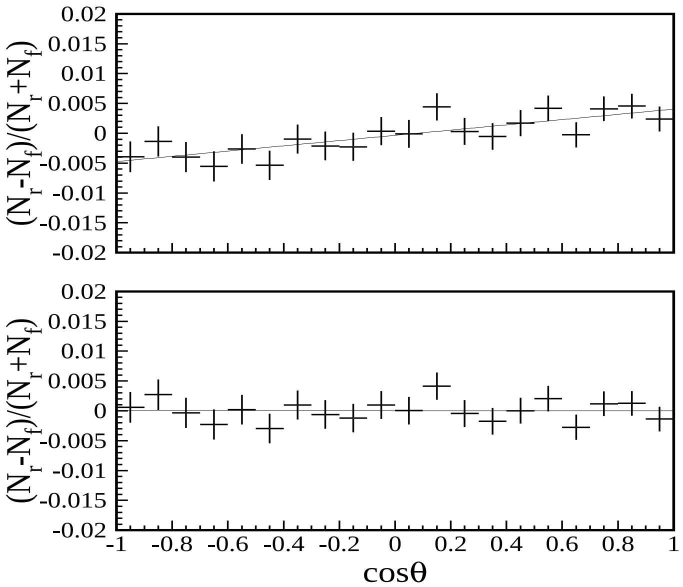
- **Comparing With Other Experimental Results**
  - α_Ω from *HyperCP* has a positive sign, which is different from PDG value and other experiments.
  - The result of α_Ω from *HyperCP* is nonzero (7.2σ).



Preliminary Measurement of $\alpha_{\overline{\Omega}}$ and *CPV* Test

- **Using the same code and event selection cuts, we have analyzed 1.9 million $\bar{\Omega}^+ \to \bar{\Lambda} K^+$, $\bar{\Lambda} \to \bar{p}\pi^+$ events.**





- **Preliminary Results of $\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}$ and $\alpha_{\overline{\Omega}}$**

$$\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}} = [1.16 \pm 0.18(\mathrm{stat})] \times 10^{-2}.$$

Using the PDG value of $\alpha_{\overline{\Lambda}} = -0.642 \pm 0.013$, $\alpha_{\overline{\Omega}}$ was extracted:

$$\alpha_{\overline{\Omega}} = [-1.81 \pm 0.28(\mathrm{stat})] \times 10^{-2}.$$

- ***CPV* Test For $\Omega \to \Lambda K$ Decays**

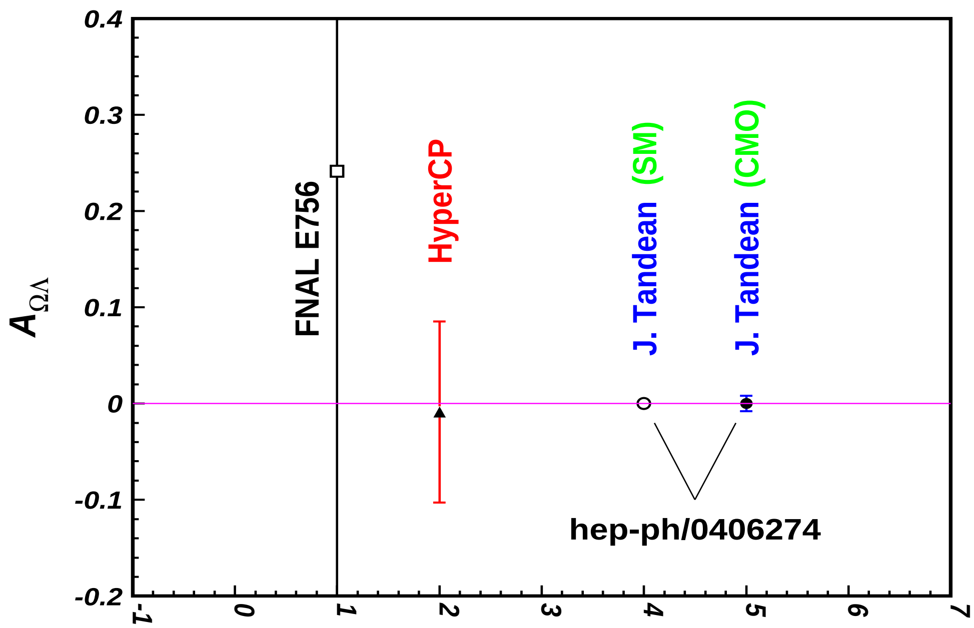
Using the measured values of $\alpha_{\Omega}\alpha_{\Lambda}$ and $\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}$, asymmetries are determined to be

$$\delta_{\Omega\Lambda} \equiv \alpha_{\Omega}\alpha_{\Lambda} - \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}} = [-0.02 \pm 0.22(stat)] \times 10^{-2},$$

$$A_{\Omega\Lambda} \equiv \frac{\alpha_{\Omega}\alpha_{\Lambda} - \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}}{\alpha_{\Omega}\alpha_{\Lambda} + \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}} = [-0.87 \pm 9.41(stat)] \times 10^{-2}.$$

***CP* is conserved within statistics**

- $A_{\Omega\Lambda}$ **From Other Measurements and Theoretical Predictions**
  - $A_{\Omega\Lambda}$ for FNAL *E756* in the plot is extrapolated from their measurements, $\alpha_{\Omega} = -0.028 \pm 0.047$ and $\alpha_{\overline{\Omega}} = +0.017 \pm 0.077$.
  - In Tandean's predictions, *SM* stands for the standard model, and *CMO* stands for chromomagnetic-penguin operators which includes possible physics beyond the standard model.

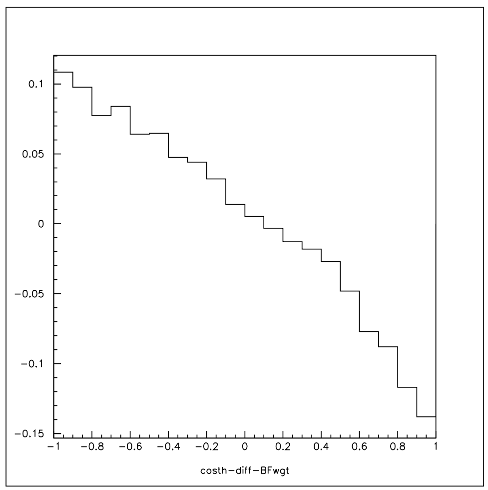


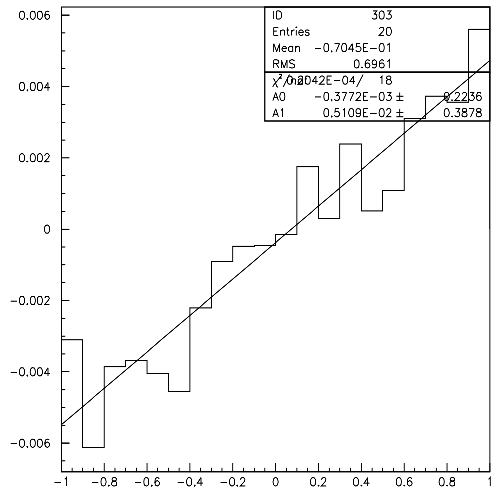
Conclusions

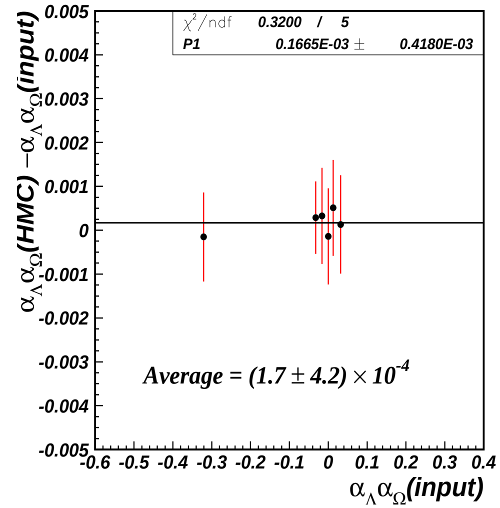
- With the largest sample of hyperon decays ever recorded, HyperCP has precisely measured the decay parameters: β_Ξ, γ_Ξ and α_Ω.
- The $\Lambda\pi$ scattering strong phase-shift difference deduced from the measured β_Ξ and PDG α_Ξ is nonzero and is comparable to the one of $p\pi$ scattering, which indicates *CPV* in $\Xi \to \Lambda\pi$ decays may not be suppressed compared to that in $\Lambda \to p\pi$ decays.
- We find the first evidence of a nonzero α_Ω, and hence parity violation in $\Omega \to \Lambda K$ decays.
- No *CP*-violation is observed in the joint decays of $\Omega \to \Lambda K \to p\pi K$ at the level of 0.22×10^{-2} for $\delta_{\Omega\Lambda}$ and 9.41×10^{-2} for $A_{\Omega\Lambda}$.

The Sign of α_Ω

- The same analysis code was used to analyze 78,000 events of the $\Xi^- \to \Lambda\pi^-$ decay, $\alpha_\Xi\alpha_\Lambda = -0.286 \pm 0.007$, both the sign and value are consistent with PDG.

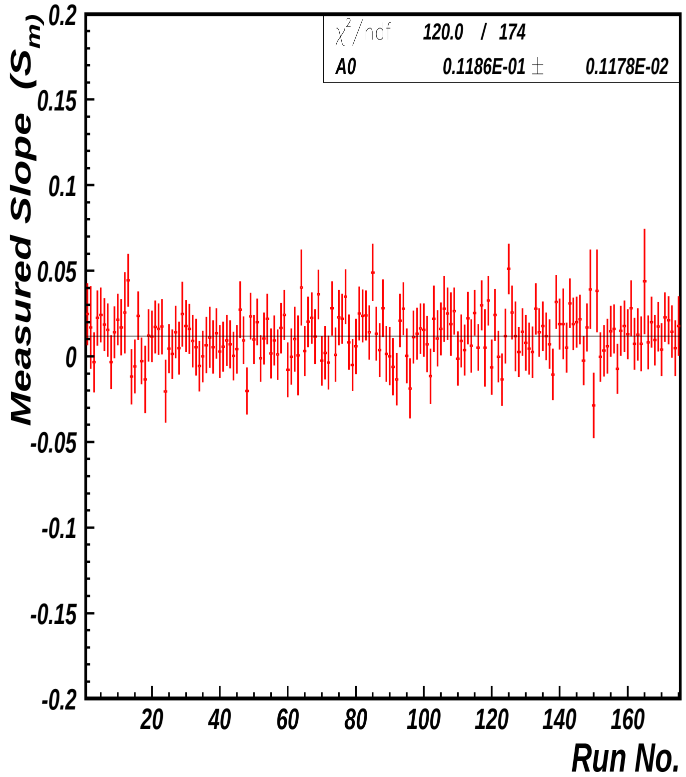


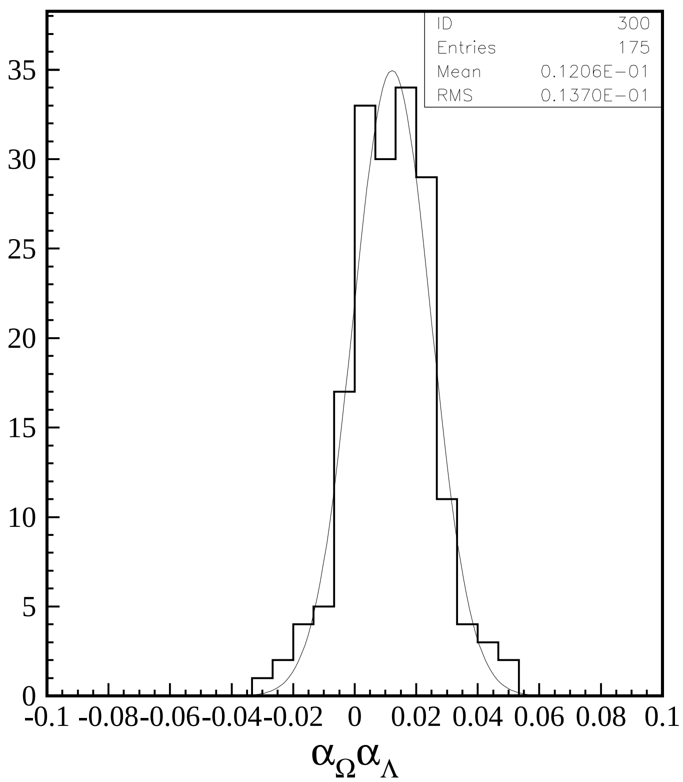




- Monte-Carlo Study: HMC results consistent with input values both on the sign and value.

- Individual run by run analysis shows only 29 out of 175 runs have negative $\alpha_\Omega \alpha_\Lambda$ values but all with very large statistical errors compared with their values.





Systematic Study of β and γ

- **Systematic Errors**

Systematic Study	S_x $(\times 0.00019)$	S_y $(\times 0.00017)$
Accidental hits	0.28	0.06
Background	0.06	0.22
Detector efficiency	0.39	0.50
Precession angle	0.58	0.17
Event selection	0.61	0.64
Total error	0.97	0.86